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Tensile properties and fracture locations of friction-stir welded joints of 6061-T6 aluminum alloy

HUIJIE LIU
Joining and Welding Research Institute, Osaka University, Osaka 567-0047, Japan; National Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 150001, People's Republic of China
E-mail: lhj@jwri.osaka-u.ac.jp; liuhj@hope.hit.edu.cn

H. FUJII, M. MAEDA, K. NOGI
Joining and Welding Research Institute, Osaka University, Osaka 567-0047, Japan

Friction stir welding (FSW) can eliminate some of the welding defects, such as cracking and porosity, which are often associated with fusion welding processes [1, 2]. Therefore, it is being used to weld heat treatable aluminum alloys that are difficult to fusion weld [3, 4], including the 2xxx [5–8], 6xxx [9–18] and 7xxx series [6, 19]. Concerning the FSW of the 6xxx series aluminum alloys, 6063-T5 aluminum alloy joints have been studied with respect to their microstructures [9, 10], tensile properties and fracture locations [11], but the effects of the welding parameters on them have not been reported. Okamura *et al.* [12] and Kumagai *et al.* [13] examined the tensile properties of 6061-T5 aluminum alloy joints. All the tensile properties, including ultimate strength, proof strength and elongation, did not change in a wide range of revolutionary pitches from about 0.2 mm/r to 0.8 mm/r. The microstructures [14, 15] and tensile properties [16, 17] of 6061-T6 aluminum alloy joints were also studied, but the effects of the welding parameters on the tensile properties and fracture locations of the joints were not examined in detail. This letter reports on the study of the FSW of 6061-T6 aluminum alloy, with the emphasis placed on the tensile properties and fracture locations of the joints welded with different welding parameters.

The base material used in this study was a 5-mm-thick 6061-T6 aluminum alloy plate, and its chemical composition and mechanical properties are listed in Table I. The plate was cut and machined into rectangular welding samples 300 mm long by 80 mm wide, and the samples were longitudinally butt-welded using a FSW machine. The designated welding tool size and welding parameters are listed in Table II. After welding, the joints were cross-sectioned perpendicular to the welding direction for metallographic analyses and tensile tests using an electrical-discharge cutting machine. The cross-sections of the metallographic specimens were polished with an alumina suspension, etched with Keller's reagent and observed by optical microscopy. The configuration and size of the transverse tensile specimens were prepared with reference to JIS Z2201. The Vickers hardness profiles across the weld nugget (WN), thermo-mechanically affected zone (TMAZ), heat affected zone (HAZ) and partial base material were measured along the centerlines of the cross-sections of the tensile specimens using a load of 0.98 N for 10 s, and Vickers indentations with a spacing of 1 mm were used to determine the fracture locations of the joints. The tensile tests were carried out at room temperature at a crosshead speed of 1 mm/min using a computer-controlled testing machine, and the tensile properties of each joint were evaluated by three tensile specimens cut from the same joint.

Fig. 1 shows the tensile properties and fracture locations of the joints welded at different revolutionary pitches. It can be seen from Fig. 1a that the tensile properties of each joint are all lower than those of the base material (see Table I). Especially, the elongation of the joint is considerably low, its maximum is merely equivalent to 37% that of the base material. When the revolutionary pitch is smaller than 0.53 mm/r, the ultimate strength and 0.2% proof strength increase with the revolutionary pitch. On the other hand, when the revolutionary pitch is greater than 0.53 mm/r, all the tensile properties tend to decrease with increasing revolutionary pitch. These results indicate that a softening effect has taken place in the 6061-T6 aluminum alloy due to the FSW. The softened levels or tensile properties of the joints are significantly affected by the welding parameters. The optimum welding parameters can be determined from the relation between the tensile properties and the welding parameters. For example, the revolutionary pitch of 0.53 mm/r, corresponding to the rotation speed of 1500 rpm and the welding speed of 800 mm/min, is optimum for the tensile properties of the joints. In this case, the ultimate strength of the joint is equivalent to 77% that of the base material.

In Fig. 1b, the fracture location of the joint is expressed by the distance from the weld center, and the retreating side and advancing side of each joint are denoted by RS and AS, respectively. When the revolutionary pitch is smaller than 0.53 mm/r, the fracture locations of the joints are distant from the weld center, and the distance from the weld center decreases with increasing revolutionary pitch. When the revolutionary pitch is greater than 0.53 mm/r, the fracture locations of the joints vary slightly, and they are at a distance of 2.3–2.6 mm from the weld center. These results indicate that

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TABLE I Chemical composition and mechanical properties of 6061-T6 aluminum alloy

Chemical composition (wt%)									Mechanical properties		
Al	Si	Fe	Cu	Mg	Mn	Ti	Zn	Cr	Ultimate strength	0.2% proof strength	Elongation
Bal.	0.62	0.33	0.28	0.90	0.06	0.02	0.02	0.17	309 MPa	278 MPa	13.0%

TABLE II Tool size and welding process parameters used in the experiments

Tool size (mm)				Welding parameters		
Shoulder diameter	Pin diameter	Pin length	Tool tilt	Rotation speed	Welding speed	Revolutionary pitch
15	6	4.7	3°	1000–1500 rpm	100–1000 mm/min	0.07–1.00 mm/r

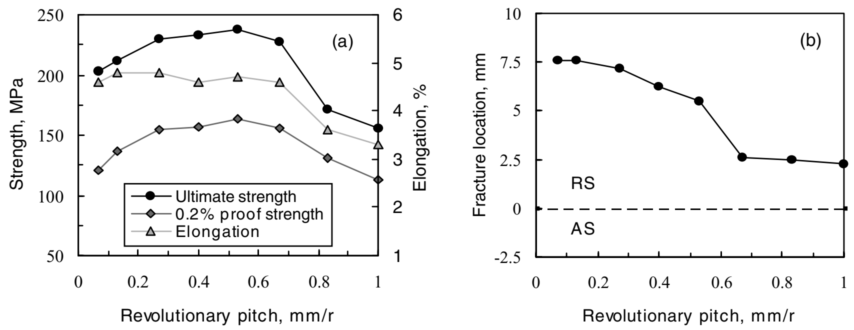

Figure 1 Tensile properties and fracture locations of the joints welded at different revolutionary pitches: (a) tensile properties and (b) fracture locations.

the fracture locations of the joints are also affected by the welding parameters. Moreover, it should be noted that none of the joints are fractured on the advancing side. This implies that the tensile properties of the joints are not the same on the two sides of the weld center, and the retreating side is weaker than the advancing side.

The tensile properties and fracture locations of the joints are related to the hardness profiles and welding defects in the joints [20], and the hardness profiles and welding defects are related to the welding parameters. Figs 2 and 3 show, respectively, the typical cross-sections and microhardness profiles in the joints welded at different revolutionary pitches. When the revolutionary pitch is smaller than 0.53 mm/r, the FSW produces defect-free joints (see Fig. 2a and b). In this case, the tensile properties and fracture locations of the joints are dependent only on the microhardness profiles in the joints. It can be seen from Fig. 3 that a hardness degradation region, i.e. softened region, has occurred in each joint, thus the tensile properties of the joint are lower than those of the base material. There are two low-hardness zones on the two sides of the weld center, but the minimum hardness value exists in the low-hardness zone on the retreating side, accordingly the joint is fractured on the retreating side. Moreover, the minimum hardness value increases as the revolutionary pitch increases, consequently the ultimate strength and proof strength of the joint increase with the revolutionary pitch. Comparing Fig. 2 with Fig. 3, it can be found that the minimum hardness occurs in the HAZ adjacent to the TMAZ on the retreating side. Therefore, the joint is practically fractured in the HAZ on the retreating side, and the fracture surface is parallel to the TMAZ/HAZ interface on the retreating side.

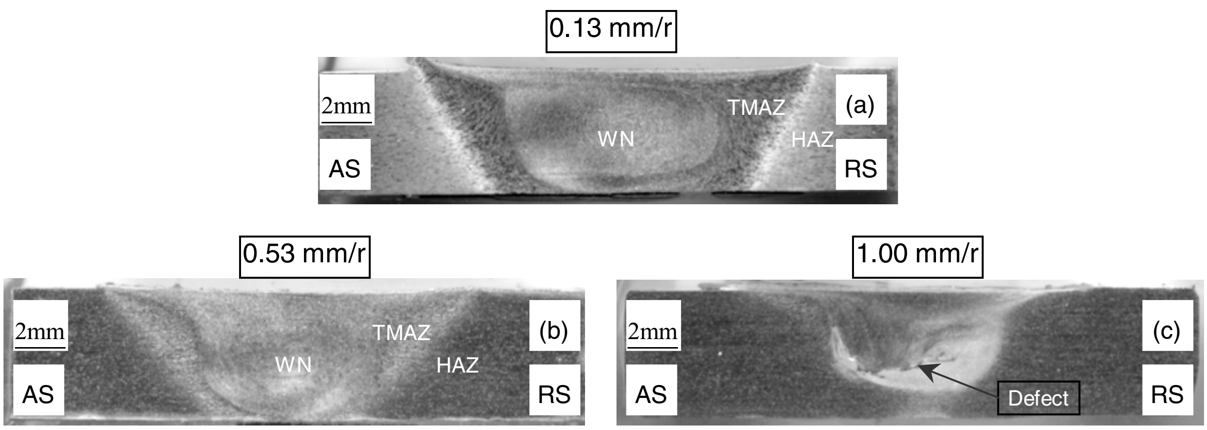

Figure 2 Cross sections of the joints welded at different revolutionary pitches: (a) 0.07 mm/r, (b) 0.53 mm/r and (c) 1.00 mm/r.

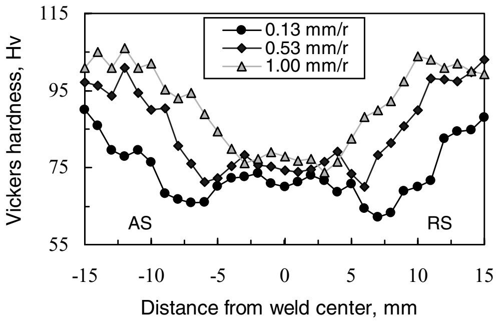

Figure 3 Hardness profiles in the joints welded at different revolutionary pitches.

On the other hand, when the revolutionary pitch is greater than 0.53 mm/r, a crack-like defect is formed in the lower half of the joint for lack of heat input to the joint (see Fig. 2c). In this case, the tensile properties and fracture locations of the joint are significantly affected by the defect. The mismatched deformation between the partial weld beneath the defect and the other partial weld above the defect leads the joint to fracture in two stages. First, the partial weld beneath the defect is fractured at the original interface between the two welding samples, and then the residual weld above the defect is fractured near the edge of the weld nugget on the retreating side. Therefore, the tensile properties of the joint seriously deteriorate, and the fracture location of the joint is confined to the weld nugget in which the defect exists.

In summary, the tensile properties and fracture locations of 6061-T6 aluminum alloy joints are significantly affected by the FSW parameters. The optimum revolutionary pitch is 0.53 mm/r corresponding to a rotation speed of 1500 rpm and a welding speed of 800 mm/min, and the maximum ultimate strength of the joint is equivalent to 77% that of the base material. When the revolutionary pitch deviates from the optimum value, a crack-like defect or serious softening is produced in the joints, thus the tensile properties of the joints degrade. When the joints are free of defects, they fracture in the HAZ on the retreating side. Otherwise, when a crack-like defect exists in the joints, the fracture occurs in the weld nugget.

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